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Linking water research with the sustainability of the human–natural system

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The sustainability of the coupled human–natural system under continuous global warming has been capturing increasing research interest. Water is among the most critical elements, not only for the natural system but also for social–economic development, especially in water-limited regions. In this paper, we provide a comprehensive analytical framework to link water research with the sustainability of the human–natural system. We suggest that special emphasis should be paid to the linkage analysis between social and biophysical water components. We also describe the importance of combined usage of different research methods in the framework. This framework aims to provide a scientific basis of issues of the sustainability of the coupled human–natural system (CHANS), including the potential conflict between supply and demand of water for nature and human beings, the impact of climate change and human activities on the water distribution in CHANS, and the trade-offs of water-related ecosystem services in CHANS.

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Introduction

The sustainability of the coupled human-natural system (CHANS) under continuous global warming catches increasing research interest. It is one of the central issues of on-going international research programmes and committees, for example the Millennium Ecosystem Assessment (2001) and Future Earth (2015). Water is among the most critical elements in CHANS linking nature and human beings [1••]. It impacts the sustainability of CHANS by the distribution of available water resources among the natural and social–economic sectors in CHANS. Sustainable water use is also the sixth goal established by the United Nations to guide global development in 2030. Water is the limiting factor for natural–social development. Exponentially growing human water demands [[1••]] and increasingly uncertain hydrologic regimes due to climate change and land use change [3•] put available water resources under great pressure. The water problem is even more serious in arid and semi-arid regions, which comprise approximately 30% of the terrestrial area. For instance, desertification and oasification in arid and semi-arid regions are largely related to the shortage or abundance of water resources. The rapid expansion of irrigated farmland has caused tributaries downstream to dry up [4]. The reduction of precipitation and the overconsumption of drinking water have dropped the groundwater level, triggering a series of ecological and environmental problems [5].

Studies on the hydrological process of natural ecosystems (e.g., wetlands, forest, grassland and shrub) have made outstanding progress [6–8]. From the mid-20th century onwards, the impact of human activities in perturbing the water-related ecosystem structure and function [17,18] caused research to take note, with the focus on the impact of excessive grazing, irrational deforestation and over-exploitation of aquifers, etc. Linkage of water research with the sustainability of the human–natural system starts from the integrated modelling approach, nesting hydrological modelling with the social–economic activities of human being [9,10•]. With the increasing demand of linking water research with the sustainability of CHANS, conceptual tools, models and disciplines of the research (e.g., socio-hydrology, virtual water, food–energy–water nexus [11], environmental flows) were raised to integrate ecological processes with the dynamic of environment and society [12].

Current progress shows that water research is in the corner of changing from the traditional hydrological processes of ecosystems to the linkage with the sustainability of the human–natural system. It is worth noting that the process

and function of the CHANS is complex, varying across spatio-temporal scales and organizational units [13], and manifests diverse complexities of human–nature interactions, such as heterogeneity, non-linearity, feedbacks, and resilience [13,14]. The complex nature of CHANS asks for the continuous improvement of the hydrological research, as well as for the reduction of the accumulated uncertainty in the nesting hydrological modelling of social–economic activities. It also asks for the rethinking of water research from a more comprehensive perspective in the next step of research.

Framework of water research of CHANS

The sustainability of CHANS takes a comprehensive view of water needs across sectors of natural ecosystems, agriculture, industry and domestic water use [15]. It can be concretely represented by integrating human water uses into the larger scope of ecological and environmental maintenance, or the provision of water within rivers to support positive ecological and environmental outcomes while maintaining the water needs of human society [16]. A water analysis of CHANS is related to both available water resources and the distribution of water in different sectors of CHANS. The available water is fundamental to the functions of CHANS [2]. It depends on the hydrological process of the ecosystem, with the related indicators being runoff, soil moisture, snowmelt and so on. Water distribution reflects the status of different functions in CHANS. It can be categorized as green water, irrigation water, social–economic water and so on. Green water refers to precipitation water supporting plant growth [17]. Green water is an important requirement for maintaining the ecosystem services (ES) of the natural part of CHANS, for example, carbon sequestration, soil conservation, and evaporative cooling. Irrigation water is the most prominent form of human water use. It accounts for approximately 70% of water withdrawals from runoff as a global estimate [18]. Irrigation water directly impacts ecosystems, for example, by improving vegetation productivity and potentially causing the salinization of the land [19]. Social–economic water utilization, further divided into municipal, industrial, environmental, energy-related, and livestock water use, is related to the level of national development, regional environmental policies, people's living standards and population density [20]. The environment flow is the water flows that are required to sustain freshwater, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them [21]. Water has attributes of quantity, quality, location, and timing of flow [22]. The matching of available water resources and the water demand in these attributes is essential to the maintenance of the functions and hence the sustainability of CHANS.

Water research of CHANS is closely related with the current progress. For example, evapotranspiration, including vegetation transpiration and soil evaporation, can be measured at points and at the field scale, using weighing lysimeters, energy balance and the Bowen ratio and sap flow. The application and development of thermal infrared remote sensing technology allows the research on evapotranspiration to be extended to the region scale. Surface soil moisture data have been monitored by the Soil Moisture and Ocean Salinity (SMOS) mission [23] and the Soil Moisture Active Passive (SMAP) mission [24] recently. Deep soil moisture mainly depends on field sampling or hydrological model simulation [25]. Streamflow data are measured at hydrological stations, while they can also be simulated with hydrological models [9].

The sustainability of CHANS is often the harmonization of natural water availability with social and economic water consumption [26,27]. Water research of CHANS asks the special emphasis be paid to the linkage analysis between biophysical and social water components. While a number of frameworks and indices that account for both biophysical and social factors exist, they are often more theoretical than practical. For example, available water resources are compared to a fixed minimum water requirement, which fails to account for variability in demand and water management practices [28]. New indicators and methods are still needed for the full consideration of demand, endowment, infrastructure, and institutional characteristics. Furthermore, the linkage analysis requires time and space connections between biophysical and social water processes. The assimilation of water processes in the integrated natural and social–economic systems over multiple scales would improve the efficiency of the linkage analysis.

We contend that existing technologies can be reframed, and emerging technologies are expected to create effective integrated water management in CHANS, in particular the combined application of remote sensing monitoring, surface field observations and modelling. Remote sensing technology has an advantage in obtaining temporal and spatial variations of the earth's surface. In particular, current satellite observations have accumulated long-term data over more than four decades. Remote sensing technology provides surface data of not only natural ecosystems (e.g., land cover, vegetation cover and structure, snow water, soil moisture, and surface temperature) but also social–economic data. The satellite-derived night-time light data (e.g., DMSP/OLS, NPP-VIIRS) are efficient in detection of urban expansion [29], the spatial distribution of the gross domestic product [30], population density [31], electric power consumption [32] and so on. Ground observations (e.g., river runoff) are treated as a credible data source for discovering the mechanism of CHANS processes, which provides the theoretical basis for model construction. Moreover, it can be utilized in the CHANS analysis in (1) model calibration to determine the model parameters in a

particular study area; (2) as a supplement to remote sensing data (e.g., interpretation signs of remote sensing); and (3) validation of model results. Modelling is the tool for scenario analysis and prediction of CHANS. Thus, the rapid development of data assimilation is supposed to benefit water research of CHANS [33]. Current studies have explored data assimilation methods to integrate various existing observations from the ground and satellites into hydrological models [34–36]. Assimilated observation data include satellite-derived soil moisture and evapotranspiration, as well as streamflow observations. Data assimilation has proved to improve hydrological predictions, for example, flood forecasting, in data-scarce regions. A growing number of studies have also assimilated terrestrial water storage derived from the Gravity Recovery And Climate Experiment (GRACE) to obtain a better understanding of surface and subsurface processes related to water redistribution within the Earth system [37]. In our opinion, water research in the context of CHANS is expected to extend data assimilation from the current content to further applied observed social–economic data in the human and natural coupled process.

Water research of CHANS aims to directly answer the questions related to the possible conflict between supply and demand of water resources in CHANS. Human activities are exerting increasing impacts on the environment on all scales, outcompeting natural processes in many ways. For example, developing countries around the world are expanding hydropower to meet growing energy demand. The construction of China's South-North Water Diversion Project is to ease the crisis of water resources in northern China. In the Brazilian Amazon, >200 dams are planned over the next 30 years [38]. On the other side, climate change causes the frequency of extreme events, such as extreme precipitation and extreme drought, to change. The frequency of extreme precipitation events in many countries, such as the United States and Canada, has increased. The effects of climate change and human activities are often intertwined, which has already been revealed by nonlinear time-series analysis methods [39•]. It is worth noting that the impact of drought and floods on agriculture, ecology and industry are not adequately reflected by average or annual water volumes [22]. The available water in the incorrect time or place will lead to a contradiction between supply and demand of water resources. Seasonal abnormal precipitation at the critical period of crop growth, including emergence and sprouting or heading and flowering, directly affects the rational allocation of crops and high and stable yields [40]. Thus, special attention should be paid to studies on a monthly scale, a daily scale or even shorter.

The existing water research that simultaneously concerns on human and natural factors has delivered undoubted benefits to people around the world, but equally, we need to consider wider sustainable development goals in the context of CHANS. In addition to the aforementioned critical gaps, there are also some gaps raised by current studies, such as extreme events and resilience [41], water conflict in transboundary rivers [42] and limited governance capacity for water management in developing countries [43].

Moreover, since water is directly related with different ecosystem services [22], ES trade-offs, that is the increase of one ES at the expense of the decrease of other ES, are another important issue of sustainability of CHANS in the framework. For example, increasing water consumption resulting from the expansion of agricultural land reduces blue-water availability for humans and ecosystems downstream. Trade-offs can also occur between the acquisition of present and future services. For instance, the pollution of surface water for short-term economic benefits can directly impact the suitability of fresh water resources for drinking and other human uses in the future [44]. In the scenarios studies, both the ES trade-offs and the available water act as the limiting factors in determining the possible distribution of water resources in different sectors of CHANS [45]. It is also deemed sustainable for the scenarios of maximum ecological and economic benefits with less water cost. The study objective of on ES relationships in the content of CHANS could be firstly, the exploration of water constraints to landscapes multifunctional ability; secondly, the spatial and temporal flow of ecosystem services that make trade-offs between water providing and benefiting sectors; and thirdly, the support of environmental planning, watershed management and policy decisions. It is worth noting that there were conflicts between the optimal scenarios at the watershed scale and the township scale, suggesting that the object and the spatial-temporal scale should be taken into consideration in environmental planning and policy decisions using ecosystem services trade-offs [46••].

Conclusion

In the context of the global climate change and the intensification of human activities, water research is in the corner of changing from the traditional hydrological process of ecosystems to the linkage with the sustainability of CHANS. In this study, we propose a general framework to meet this research requirement. The framework is closely related to the current progress of water research; however, it asks that special emphasis be paid to the linkage analysis between biophysical and social water components. The development of data assimilation in the combined application of remote sensing monitoring, surface field observations, and modelling methods is also essential. The framework emphasizes the need to explore the answer of questions in the context of the sustainability of CHANS, including the impact of climate change and human activities on water distribution and the trade-offs of water-related ecosystem services.

Conflicts of interest

The authors have no conflicts of interest to declare.

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